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Laser and Particle Beams

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OVERVIEW OF VIRTUAL NATIONAL LABORATORY OBJECTIVES, PLANS, AND PROJECTS*

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ABSTRACT

Significant experimental and theoretical progress has been made in the U.S. heavy ion fusion program on high-current sources, transport, and focusing. Currents over 200 mA have been transported through a matching section and 10 half-lattice periods with electric quadrupoles. An experiment shows control of high beam current with an aperture, while avoiding secondary electrons. New theory and simulations of the neutralization of intense beam space charge with plasma in various focusing chamber configurations predict that near-emittance-limited beam focal spot sizes can be obtained even with beam perveance (ratio of beam space potential to ion energy) >10 x higher than in earlier HIF focusing experiments. Progress in a new focusing experiment with plasma neutralization up to 10^{-3} perveance, and designs for a next-step experiment to study beam brightness evolution from source to target are described.

1. INTRODUCTION

Demonstration of inertial fusion ignition and energy gain in the laboratory is expected with the National Ignition Facility (NIF), which will provide the scientific basis for the target physics for inertial fusion energy (IFE). In addition, IFE will require development of efficient and affordable drivers, mass-produced high-gain targets, and long-life, low-activation chambers for 5 to 10 Hz pulse rates. Heavy-ion accelerator-driven power plants are an attractive IFE approach because (a) published HIF target designs exist with more than adequate gain, and 2-D hydrostability (see paper by Callahan), (b) thick-liquid protected chambers (see paper by Peterson) are compatible with indirect-drive illumination geometry, (c) cryo-fuel capsules injected into hot chambers are protected within hohlraums (see paper by Goodin), (d) high energy particle accelerators of MJ-beam energy scale have exhibited intrinsic efficiencies, pulse rates, power levels, and longevity required for IFE, and (e) the clear-bore magnets used to focus heavy ions should tolerate target debris and can be well-shielded to target neutron and gamma radiation (Peterson). For U.S. HIF driver research based on induction linacs, the main new challenge is accelerating, transporting and focusing intense heavy ion beams with high line-charge density (of order 0.1 μC/m at injection to >10 μC/m at final focus with associated high space-charge beam potentials of > 1 kV to 100 kV, respectively).

Heavy ion fusion driver research in the U.S. is carried out primarily under the auspices of the Heavy Ion Fusion Virtual National Laboratory (HIF-VNL) by Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), and Princeton Plasma Physics Laboratory (PPPL), closely coupled to other HIF beam science research carried out by the University of Maryland, Mission Research Corporation, and the University of Missouri.

Heavy ion fusion-related chamber and target development is carried out through the Virtual Laboratory for Technology (VLT) at the Lawrence Livermore National Laboratory, General Atomics, Sandia National Laboratories, Massachusetts Institute of Technology, Georgia Institute of Technology, and the University of California at Berkeley, San Diego and Los Angeles.

2. CURRENT HIF DRIVER RESEARCH

Particle-in-cell simulations are in good agreement with past low current (mA level) beam experiments in transport (TIEFENBACK 1986, FAWLEY *et al*. 1997, SEIDL *et al*. 1998) and focusing (MACLAREN *et al*.2002*)* in which the dimensionless beam perveance (space-charge potential/ion kinetic energy) was of driver scale for injection. The U.S. fusion program has now embarked on three new experiments at about 100 x greater line-charge-density than in the previous scaled-beam experiments in the HIF program:

(1) *The High Current Experiment (HCX)*, Figure 1, which began operation in January 2002, will study dynamic aperture limits, emittance growth, halos, steering, and wall/secondary electron interactions with a 1-1.8 MeV, 300–600 mA K^{+1} ion beam, starting

with 10 electric and four magnetic quadrupoles. The single-beam HCX will be the first heavy ion electric and magnetic quadrupole transport experiment with the high line charge density ($\lambda \sim 0.1$ -0.25 μC/m) and pulse duration (4.5 $< \tau <$10 μs) expected in a driver. It will have a coasting beam at an injection energy $1.0 < E < 2.0$ MeV (K+). The values of these variables, for a driver, are presently believed to lie in similar broad ranges: $0.1 < \lambda < 1.0$ μC/m, $5 < \tau < 50$ μs, and $1 < E < 4$ MeV at injection. One of the primary goals of the HCX will be to answer the above scientific questions that would enable appropriate choices of machine apertures and spacing of beam centroid corrections needed for high-confidence and attractive driver designs. Initial results will be reported for transport through the first 10 electric quadrupoles. (See papers on HCX experiments by Seidl and on HCX theory/simulation by Lund)

(2) **The Neutralized Transport Experiment (NTX)** under construction, Figure 2, will use a 400 keV, 80 mA K^{+1} ion beam to study perveance limits to final focus as well as plasma neutralization in various chamber configurations. The measured NTX gun beam quality ($\varepsilon_n < 0.1$ π mm-mr) is more than adequate to allow spot-size differences between 90 and 95 % space-charge neutralization to be distinguishable. (see paper by Henestroza).

(3) **Merging beamlet injector**. A novel injector concept with merging beamlets will be tested at > 500 mA total current on a recently completed STS 500 kV test stand at LLNL (Figure 3). A new high-brightness and high-current-density Argon plasma source (100 mA/cm^2) on an LLNL STS 100 kV test stand will be described. (See paper by Ahle)

University of Maryland HIF Research

Nonrelativistic electron beams at 10 keV and $\sim$ 100 mA can be used to experimentally simulate the space-charge-dominated beam dynamics of heavy ion beams that may be used in a future heavy ion power plant. A recirculating ring of such electron beams under construction at the University of Maryland can be used to study long-path issues over many hundreds of focusing lattice periods at low cost (see poster by O'Shea and Kishek). The long-path issues include transverse and longitudinal temperature equipartition, mixing and dissipation of perturbations, instabilities, emittance, and halo growth.

Enabling technology for HCX

Superconducting Magnet Development. Present superconducting transport lattice designs center on magnet/cryostat systems being developed by the VNL laboratories and external partners (MIT, Advanced Magnet Laboratory, LLNL and LBNL) suitable for a transport experiment using the HCX beam described above. The present designs have a period of 2L = 45 cm, a quadrupole occupancy of $\eta = 0.5$, and superconducting wire at a radius of $r_w = 3.5$ cm with a peak field in the conductors of 6-7 Tesla. Prototypes of two different designs were successfully tested in 2001. In 2002 we are also developing a unit transport cell consisting of two quadrupoles sharing a common dewar, in a cryostat configuration compatible with acceleration gaps.

Room Temperature Magnet Development. Four room temperature, pulsed magnets will be used in HCX to begin the study of high-current beam transport in magnetic quadrupoles. These quadrupoles were originally fabricated for a prototype array magnet, and provide lower gradient (than is required in HCX). A high-gradient, pulsed magnet design study is being developed for comparison with the superconducting designs.

Induction Core Development. Extensions of the HCX under consideration include acceleration and bunch compression. This requires quality cores that can produce reliable, long-pulse duration waveforms. A bunch control induction module will be integrated into HCX for experiments in 2003-2004. Other ongoing efforts include the continued evaluation of alloys for induction cores. Several coatings have been tested that allow induction cores to be annealed after winding, and most have demonstrated adequate voltage holding.

Theory and Modeling

The HIF program has developed unique simulation tools to explore the relevant physics areas. Our codes are characterized by their methods and regimes of applicability:

1. Follow particles (plasma particle-in-cell method):

WARP (driver) (FRIEDMAN *et al.* 1992, GROTE *et al.* 2001): 3-D (or r, z or x,y) electrostatic (ES), detailed lattice. This code offers a detailed beamline description but is suitable for studies of propagation over long distances. It uses novel "cut-cell" boundaries to allow sub grid-scale resolution of internal structures. It has been benchmarked versus HIF experiments, and others.

LSP (chamber & driver) (HUGHES *et al.* 2001, SHARP *et al.* 1996, SHARP *et al.* 1993): 3-D (or r,z) implicit (or explicit) electromagnetic (EM) or

electrostatic(ES),hybrid (kinetic/fluid). This well-benchmarked code is optimized for the study of systems with a wide range of scales and high-density plasmas. It has been benchmarked on a variety of applications inside and outside HIF.

2. **Follow particles and perturbation (δf) to the beam distribution function**:

BEST (chamber & driver) (QIN et al.2000, STARTSEV et al. 2002, WELCH et al.2001 Nucl. Instr. and Meth. Phys. Res. A464, 134): 3-D EM, Darwin, or ES. This code uses a nonlinear-perturbative formulation to minimize the discrete-particle noise. As such, it is especially suitable for detailed studies of modes on a beam, where the structure of the modes is of significance. It is serving as a test bed for the development of a novel magneto-inductive (Darwin) model. It has been benchmarked versus experiments on the Los Alamos Proton Storage Ring (PSR) experiment.

1. *Evolve moments of distribution function*:

CIRCE & HERMES (driver) (DE HOON et al. 2002, FRIEDMAN 2001): transverse moments, longitudinal Lagrangian fluid. These models exist within the WARP framework (CIRCE also runs stand-alone), and couple transverse "envelope equations" at multiple "slices" of a long beam by means of Lagrangian fluid equations. The models differ in their internal representations; both are useful for scoping and synthesis, *e.g.* for drift-compression and pulse shaping.

A key strategic goal of the program is an integrated and detailed source-to-target simulation capability (Figure 4). Improved theory and simulations allow analysis of collective effects, halo generation, and ion-electron interactions over many lattice periods. (See paper by Davidson). Improved particle-in-cell codes enable modeling these experiments with realistic (not just idealized) beam distributions (See papers by Lund, Celata, and Friedman). The higher beam space-charge potentials attendant to these higher current experiments will allow us to study the effects of ionization of residual gas by the beam, trapping in the beam of stray electrons, and dynamical effects of these processes on the beam, such as ion-electron instabilities (see papers by Molvik and Qin). The main approach is to follow the un-neutralized beam using particle-in-cell simulations through injection, acceleration, longitudinal drift compression/bending (see paper by Lee) and final focus, and then seamlessly feed the beam distributions into a hybrid PIC code for ballistic propagation through chamber plasma to the target (see paper by Sharp). Well-understood simulations confirmed by experiments will allow analytic models (for example, see paper by Kaganovich on neutralization) to be developed and inserted into a systems code used to optimize the design of HIF drivers

and future experiments in an integrated fashion, taking into account injection, acceleration, drift compression, final focus and chamber propagation. Improved analytical theory and simulations have led to improved final focus models for drivers, with both emittance growth models in the accelerator, and the effects of emittance growth due to nonlinear residual space-charge fields in chamber propagation. If confirmed by experiments, the new focusing physics with plasma neutralization could have important implications for optimizing target designs with larger spot sizes, higher beam perveance, and fewer beams.

The area of beam loss and interaction with gas and electrons is emerging as a key area of common interest to the HIF experiments described above and high-energy ion accelerators that have comparable line-charge densities and space charge potentials (e.g., > 1 kV). An experiment with the new NTX ion beam (Figure 5) reduces the beam current by a factor of two with an aperture, while preventing the ingress of secondary electrons. (See details in paper by Henestroza). The central peak feature in the measured ion current profile shown in Fig. 5 is consistent with the simulated effects of secondary electrons back-streaming to the anode source, lowering the local space charge which limits the ion current density. Two electrodes are added adjacent to the "limiter", which eliminates the central peak in ion emission current at the bias voltage calculated to create a potential barrier to secondary electrons, both upstream and downstream of the aperture. Limiting apertures have been considered as a means to control the location of halo ions escaping the beam channel at small angles in high intensity ion rings. This experiment suggests an important method by which we may vary the beam current in our future HIF experiments, as well as pointing to a potential method to control deleterious secondary electron emission effects from scrape-off apertures in high-intensity ion storage rings.

ARIES IFE power plant study-results for HIF

For the past 18 months the ARIES power plant design group headquartered in San Diego has been evaluating feasibility issues for variety of IFE drivers, including lasers and heavy ions, and a variety of chambers, including dry wall, thin-liquid coated walls, and most recently, thick-liquid protected walls. Preliminary results so far indicate:

(1) There are severe limits to chamber temperature and gas fill for survival of injected laser-driven direct-drive targets, due to the need for smooth beta-layered DT ice layers held within very small temperature windows. Indirect drive used for HIF is more robust because hohlraums

provide thermal shielding of the capsule. (See paper by Goodin)

(2) Assisted and self-pinched mode chamber propagation can be supported with chamber pressures in the 100 milliTorr to few Torr range (see paper by Olson), but vacuum pumping between the chamber and the final focus magnets is very challenging due to the need to avoid stripping of heavy ions on gas atoms in regions with magnetic field.

(3) Recent work with a new molten salt mixture including sodium, called Flinabe, promises to greatly reduce chamber gas and beamline stripping significantly in HIF chambers with thick-liquid chambers for low-pressure ballistic neutralized focusing. Final focus magnet shielding and lifetimes for HIF with more than 12 beams per side would benefit from hohlraum designs that would allow larger focusing array angles (e.g., 24 degrees rather than 12 degrees previously). (See papers by Peterson on final focus designs, and by Callahan on progress on large-angle distributed radiator target designs).

FUTURE PLANS

To optimize near-term scientific productivity and accommodate modest fusion budget growth over the next several years, a next-step integrated beam physics experiment (IBX) is proposed, which would be an intermediate step between present experiments and a much larger Integrated Research Experiment (IRE)-see paper by Barnard. The IRE would validate prototype driver technology with multiple beams. The IBX, together with parallel supporting HIF research and enabling accelerator technology, would support a decision for a more capable IRE starting in the 2008 time frame. The IBX will provide a well-diagnosed experiment to test integrated beam dynamics models for at least one beam through the injection, acceleration, longitudinal drift compression, and final focus, with sufficient beam current to include important gas-electron interactions. As such, the IBX will make a major contribution validating integrated beam models, and will undoubtedly lead to higher confidence and more capable IRE designs. The crucial integration role of the IBX is to test the ability to achieve a high beam brightness (focusability) from source to target, and the ability to predict the final focal spot size. The final focus spot size depends on accumulated beam phase-space changes through each region of the accelerator system. The Integrated Beam Experiment will be the first experiment with all of the post-accelerator manipulations of the beam found in the driver-- drift

compression, final focus, and chamber transport. The longitudinal profile of a driver-scale beam under induction acceleration, its profile and the manipulation of that profile, and the resultant emittance changes, would be studied for the first time. Electron dynamics with acceleration would also be addressed, with the opportunity for the first time to see electron effects on beams undergoing strong acceleration and longitudinal bunch compression.

Figure 6 illustrates the major elements in an updated long-range HIF strategy, which incorporates the IBX. Note that implosion experiments in the National Ignition Facility testing symmetry begin in 2007, a few years before the IRE would begin. In addition to beam dynamics studies with the IBX, it is important to study intense heavy ion beam interactions with candidate HIF target materials over the next 8-10 years before the IRE would be operational. RF-linac-storage ring facilities can be used to study heavy-ion target interactions at 1 –10eV (see paper by Jacoby), but in addition it may be possible to carryout heavy ion target interaction experiments at smaller scale but at higher temperatures of 50 – 100 eV using high-brightness heavy ion beams generated by short-pulse lasers (See papers by Campbell, Roth, and Cowan)

CONCLUSIONS

The current U.S. heavy ion fusion program addresses major science issues for intense beams through a combination of improved theory and simulation, with separate high-current experiments in transport focusing, and injection. We are beginning to obtain exciting technical results from three new high-current experiments. An Integrated Beam Experiment (IBX) is proposed as a next step. The IBX, with enabling technology improvement, would provide the basis for an HIF Integrated Research Experiment (IRE) in parallel with NIF ignition experiments.